PAPER

An Overview of Underwater Technologies for Operations Involving Underwater Munitions

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ABSTRACT

Studies to understand the potential risks associated with underwater munitions are still in their infancy. Response actions are normally driven by risk. From an explosives safety perspective, the Department of Defense believes leaving underwater munitions in place is often the safest course of action. Additionally, the risks posed by underwater munitions (e.g., sea disposal sites) remain largely unknown. Thus, it is unlikely that munition responses requiring the recovery of underwater munitions will occur in the near future. The exception is where such munitions are determined to pose an imminent and substantial threat to human health and the environment.

This article discusses technologies that can be used to characterize underwater munition sites, including bounding the site and sampling for any release of munition constituents. It also addresses technologies that can be used for recovery operations and for the disposal of any munitions. Navigation and underwater positioning are integral to all of these operations and are discussed separately.

Introduction

Response actions are normally driven by risk, and the risks posed by underwater munitions (e.g., sea disposal sites) remain largely unknown as studies to understand the potential risks associated with underwater munitions are still in their infancy. From an explosives safety perspective, the Department of Defense (DoD) believes that leaving underwater munitions in place is normally the safest course of action. Thus, it is unlikely that munition responses requiring the recovery of underwater munitions will occur in the near future. Only imminent and substantial threat to human health and the environment will warrant action.

Regardless of the need for such action, it is useful to be familiar with available technologies for underwater munition responses. Understanding of these technologies is not widespread within the unexploded ordnance (UXO) clean-up industry, and their specific capabilities and limitations within the context of a munition response are unclear. This article identifies the technologies available for underwater munition responses and attempts to explain the requirements of successful operations.

The DoD munition response actions typically follow the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) management framework, and it is within this framework that response operations are normally performed. A munition response is defined as response actions, which include site characterization and removal actions and remedial actions to address explosives hazards, human health risks, or environmental risks. A response action can also be a determination that no removal or remedial action is required. The site characterization phase generally includes three steps: a site inspection, a remedial investigation, and a feasibility study. The site characterization phase assesses potential hazards and risk to human health and the environment. If unacceptable, a removal or remedial response is designed to mitigate the hazards or risk. Removal responses are short-term actions to mitigate immediate hazards and risk. A remedial response is the final remedy for a contaminated site. Removal and remedial response actions can range from institutional controls (e.g., use restrictions, education programs) to clean-up of UXO, discarded military munitions (DMM), or munition constituents. Munition constituents are any materials including explosives and metals originating from munitions. When a response action includes munitions disposal, the munitions must be located, identified, and disposed. The disposal may take the form of detonation in place or recovery with a predetermined final disposition.

With the exception of a few emerging technologies that can detect the presence of explosives, almost all available detection technologies focus on detecting the presence of metallic anomalies that could be munitions. For this reason, all common detection technologies are essentially metal detectors. Such commonly available detectors cannot positively discriminate buried munitions from cultural debris (e.g., nails, pipes). This remains true when these technologies are adapted for underwater detection. Other technologies (e.g., sonar arrays) have limited capabilities to detect underwater munitions but can help identify possible targets or disposal sites.

This article discusses technologies for six distinct operations in the sequence they are likely used as a munition response site advances through the CERCLA process. These six operations are mapping to understand the underwater operational environment, mapping to detect munitions, inspecting and identifying targets that may be munitions, removing identified munitions from the water bottom, disposing of the munitions, and sampling for munition constituents in the water column and sediments. Navigation and underwater positioning are integral to all of these operations and are discussed separately.

The safety of response workers, supporting personnel, and the public is a primary concern for any operation where interaction with munitions is planned or has the potential to occur. Whenever the DoD undertakes activities that involve the intentional contact with munitions or could lead to an inadvertent encounter with munitions, the activity must comply with specific requirements of DoD 6055.9-STD, DoD Ammunition and Explosives Safety Standards (DoD, 2008).

Environmental Surveys

Once archival research is complete, the initial focus for assessing an underwater munitions site is bounding of the site (i.e., defining the boundaries and developing knowledge of the munitions present) and defining the underwater environment (e.g., depth, bottom type, current). Defining the underwater environment can be considered equivalent to a site visit and helps identify technologies and design the response for the site.

An understanding of the operational environment, the capabilities, and limitations of available technologies, as well as those of response personnel can help mitigate or avoid incidents (e.g., equipment damage or loss, personnel injuries) and help quantify performance expectations. Environmental surveys provide information that help bound the size of the area to investigate and aide in evaluating detection technologies to provide an optimum approach for the specific site. Multi-beam sonar, side scan sonar, and sub-bottom profiling identify water bottom topography, locations of obstructions, and sediment thickness. Other technologies may also be used for specific tasks and include video tow, high-frequency imaging sonar, and synthetic aperture sonar (SAS).

Side scan and multi-beam sonar provide information about bottom conditions and identify potential targets or disposal areas. This information provides a basis for planning follow-on activities that will detect, identify, and inspect underwater munitions, as well as help plan any required removal or remedial actions. The usefulness of these technologies is somewhat dependent on the level of resolution provided and the ability of analysts to interpret the data. Data fidelity can be enhanced by understanding the capabilities and limitations of the systems used and using multiple, complementary systems. The limitations of commercial sonar to reliably detect munitions would normally preclude using sonar data alone as a means of verifying the presence of munitions in a given area, but they can provide important information when the munitions are proud.

Detecting Munitions

Geophysical technologies detect metallic objects on or beneath the sea floor. The ability to classify an anomaly as a munitions or not is a continuing challenge. (Bell, 2002; SERDP, 2006; U.S. Army Engineering and Support Center, 2006; Billings et al., 2008; O'Neil, 2007). Magnetometers and electromagnetic induction (EMI) technologies detect the metallic components of munitions. In-situ ion mobility spectrometry, gas chromatograph-mass spectrometry, and amplifying fluorescent polymer technologies are developmental technologies that may, one day, provide the capability to detect explosives compounds in water. Buried object scanning sonar is a new technology in advanced stages of research and development that is designed to identify metallic and non-metallic objects that are partially or completely buried. It has successfully detected 81-mm and 4.2-inch mortars buried in sand to 30 cm in preliminary testing.

Sonar technologies such as SAS, multi-beam, and side scan can, in theory, be used to locate and identify munitions, but their ability to do so reliably remains mostly untested. Some side scan sonar tests have demonstrated that the technology can image cylindrical objects the size of 6-inch naval rounds and larger but could not do so reliably (U.S. Army Engineering and Support Center, 2006). At sites where bottom conditions (mud, muck) suggest munitions burial, use of low frequency, bottom penetrating sonar can aide in determining whether buried munitions are part of the problem if they are large enough to be imaged by the system used.

Table 1 summarizes technology capabilities and lists representative commercial off-the-shelf (COTS) and government off-the-shelf systems and their relative deployment costs. This table provides a limited overview of publicly available information and information obtained from inquiries to vendors. The information in Table 1 was collected for the U.S. Army Corps of Engineers to document technologies available for underwater munitions operations. (U.S. Army Corps of Engineers, 2009)

Figure 1 shows underwater metal detection technologies as applied to munitions detection.

EMI and magnetometer sensors designed for marine work do not require any specific modifications to detect munitions. Considerations include sensor selection, platform design, survey speed, and detection capability of the sensor with respect to the size of the munitions of interest. Systems designed to be towed along the sea floor also need to consider site-specific conditions such as topography, bottom type, and obstacles. Flown systems need to manage and record the height of the sensor above the sea floor to assess sensor detection performance. EMI and magnetometer detection performance is primarily a function of the separation between the sensor and the metallic item. The performance of many EMI and magnetometer systems is well understood (SERDP, 2006; Foley, 2006; Nelson, et al., 2008).

Figure 2 shows an example of EM61 MK2 detection performance for a 155-mm projectile. Recent research (Shubitidze, 2009) demonstrates that EMI performance in fresh and salt water is the same as it is on land. It is important to note that, for typical Geonics EM61-MK2 noise levels of 1 to 2 mV, the EMI coil can be no more than about 2 m above the 155-mm projectile for reliable detection.

Positioning towed metal detectors or diver-deployed units also presents a challenge and must factor whether the data will be used simply to estimate anomaly densities in a given area or determine whether detected anomalies will require subsequent investigation or removal or disposal actions. Thus, early discussions with stakeholders are critical to establish mutually acceptable survey parameters given that sites can range from a few acres to hundreds of square kilometers and may contain hundreds of thousands of munitions, as illustrated in Figure 3. Instrument positioning is discussed separately.

At present, requirements to detect underwater munitions are few, and therefore industry's use is low, and cost and performance data are very limited. Current utilization data suggest that underwater mapping for munitions, on a per line-kilometer basis, costs between 1.5 times and 5 times more than comparable land-based mapping operations but includes costs for environmental surveys not typically required for land.

Inspecting and Identifying Munitions

Inspecting and identifying underwater munitions generally equate to putting eyes on the target. Although trained experts can normally determine whether a detected piece of metal is a munition, positive identification of a munition and its configuration, including its fuzed state, can often be made difficult by deterioration or encrustation by sea life. To make as complete identification as possible, munitions experts must be able to view the item without unnecessary risk. Use of video equipped remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) provides a safe method of placing "eyes on target" for targets at most depths. For very shallow water, divers may prove to be the best means; however, diving in and of itself increases the risks involved.

Diver inspection is the simplest and most versatile method as it puts a trained expert in direct proximity of the item of interest. This comes with the cost of having a full dive team on-site, limitations of diver bottom-time, and swimming speed. If there is one item of interest at a shallow depth, divers may be the most effective approach. However, if there are numerous items of interest or deeper water, the effectiveness of divers decreases. ROV inspections sacrifice some agility around the target but benefit from significantly reduced personnel risk, simple deployment, and the ability to operate around the clock. For practical purposes, micro-, mini-, and general-class ROVs are most likely to be used because they offer versatile deployment from vessels of opportunity and provide both real-time video feeds and limited grabber capabilities. Light work and heavy work class ROVs might be deployed in situations where inspection and removal could take place at the same time. This technology might also be used when large quantities of munitions must be addressed; however, such use would be expected to require substantially larger support

TABLE 1

Underwater munition detection technologies.

Technology		Implementability	Effectiveness/ Special Considerations	Relative Cost	Representative Systems
Metal detection	Time Domain Electromagnetic Induction (TDEM)	High: Detects both ferrous and non-ferrous metallic objects	Typical COTS TDEM systems are well suited for use in shallow underwater environments. Array platforms may be hard to control. Depth of detection can be increased minimally by increasing power output of system. Can detect small and large items	Low	Geonics EM61S MK2 Ebinger UWEX 700 series
	Frequency Domain Electromagnetic Induction (FDEM)	Medium: Detects both ferrous and non-ferrous metallic objects	Requires divers that are trained in the use of FDEM technology. Bottom time of diver must be taken into consideration. Can detect small and large items, but detection depth is limited by small coil sizes and low power transmitters. Prototype towed array detection of munitions has been demonstrated	Medium to High: Higher costs derive from man hours required for trained divers	Fisher Pulse 8X Fisher 1280-X Underwater Minelab Excalibur 1000 Garret Infinium LS Garrett Sea Hunter Mark II DetectorPro Headhunter Diver
	Fluxgate Magnetometer	High: Detects ferrous metallic objects	Fluxgate magnetometers are typically reliable, rugged, and have low energy consumption, and are less susceptible to errors. Can detect small and large items	Low	Foerster FEREX 4.032 Ebinger MAGNEX 120 LW Kokkola Dredging Co. mag array Vallon EL1303D2
	Optically-Pumped (Atomic Vapor) Magnetometer	High: Detects ferrous metallic objects	High level of industry familiarization for optically pumped magnetometers with COTS underwater units available. Can detect small and large items. Higher sensitivity (versus fluxgate) - 40% increase in detection range for given size magnetic target	Medium to High: Higher cost derives from AUV or ROV use	GTK UW mag array G 880 Cesium Marine Deep Tow Magnetometer

Continued

Technology		Implementability	Effectiveness/ Special Considerations	Relative Cost	Representative Systems
Metal detection	Proton Precession Magnetometer	High: Detects ferrous metallic objects	Low level of industry familiarization for proton magnetometer utilization for munitions work. Sampling rates must be factored into tow speed. Can detect small and large items	Low	JW Fishers Proton 4 MX500 Digital Magnetometer Discovery Underwater Proton Magnetometer
	Magnetometer-Electromagnetic Detection Dual Sensor Systems	High: Detects both ferrous and non-ferrous metallic objects	System integration and timing of signals/readings need to be carefully maintained. Can detect small and large items. Prototype underwater system still in development	Not Quantified: Cost and performance data will be generated during ESTCP demonstration	ESTCP-funded system prototype still in testing phase
Sonar	Side Scan Sonar	High: Creates image of large areas of the sea floor, but munitions must be on surface or proud, and uncluttered by nearby environmental factors such as coral, rocks, and vegetation	Will not identity munitions covered by sediment, plant growth, or rock. Can detect large items, but actual capabilities and limitations for detecting and classifying munitions are unknown	Low	Fishers SSS-100k/600K Klein 3000 Series SportScan Tritech SeaKing Towfish
	Multi-Beam Echo Sounder	High: Produces high-resolution bathymetry data throughout the survey area	Theoretically can provide enough detail to identify munitions on or proud of the water bottom, but capabilities, interferences, and limitations are untested and unknown	Low to Medium	Kongsberg EM 3002 Kongsberg EM 2000
	Dual Frequency Identification Sonar (Didson System)	High: Produces high-resolution sonar imagery—even in areas of high turbidity	Can assist ROV/AUV and divers with identification of munitions in turbid waters. Specific models can be used up to 3000 m deep. Can detect small and large items depending on system used and distance from object. Object must be on or proud of the sea floor	Medium	DIDSON

Continued

Technology		Implementability	Effectiveness/ Special Considerations	Relative Cost	Representative Systems
Sonar	Sub-Bottom Profiling	High: Allows for the identification and measurement of various sediment layers that exist below the sediment/water interface	High-resolution sub-bottom systems have been used to identify buried objects, but not likely to detect munitions unless fairly large. Not economical because 100% coverage would be needed but could possibly be deployed with other 100% coverage mapping	Medium to High	Bathy 2010 Geo Chirp Geo Chirp 3-D Imagenex DF 1030
	Synthetic Aperture Sonar (SAS)	Medium-High: Synthetic aperture sonar moves sonar along a line and illuminates the same spot on the sea floor with several pings	SAS technology is still relatively new. Munitions detection capability versus proud targets is promising, but limited demonstrations. Low frequency prototype SAS has demonstrated detection of partially buried objects	Medium	Kongsberg HISAS 1030
	Buried Object Scanning Sonar (BOSS)	High: Buried object scanning sonar generates images of objects buried in underwater sediments	Known systems are still experimental, currently demonstrated detection capabilities show very consistent detections through 30 cm of sand. Classification capabilities unknown	Medium to High	CHIRP Lab SAS 40 Channel CHIRP Lab 252 Channel
Chemical Sensors	Spectroscopy	Med: Water sampling for the detection of explosives compounds using spectroscopy technology utilizes a flow-through chamber containing a solid phase micro extraction fiber that extracts and concentrates the explosive molecules	This system of sampling is still under development. Detection capability unknown	Not relevant at this time—Still under development	
	Amplifying Fluorescent Polymer (AFP)	Med: AFP detects chemical signatures emitted from munitions	This system is still relatively new and in the developmental stages. Detection capability unknown	Not relevant at this time—Still under development	

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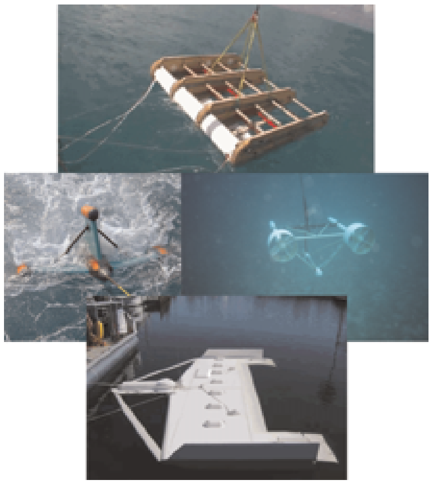
FIGURE 1

Underwater metal detecting sensors. The top image is an array of three electromagnetic induction sensors. The bottom three images show different configurations of magnetometer arrays. All are vessel-towed platforms.



resources and longer deployments. To date, only one such deployment, which will assess commercially available technology adapted for the remote recovery of munitions, is planned off the coast of Waianae, Hawaii.

FIGURE 2

EM61-MK2 sensor performance for a 155-mm projectile. The blue line marks the lowest predicted sensor response for horizontally oriented (i.e., lying flat) 155-mm projectiles. The red line marks the highest predicted response for vertically oriented 155-mm projectiles. When the item is buried at a given depth, the predicted response will be between these two curves. The black crosses are measurements taken over 155-mm projectiles in various orientations at carefully measured depths, and validate the predicted responses.

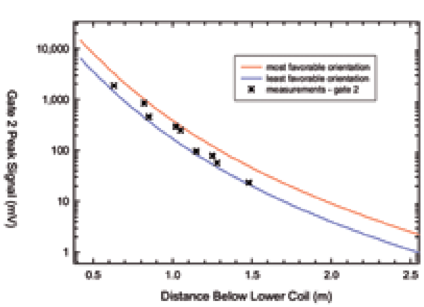
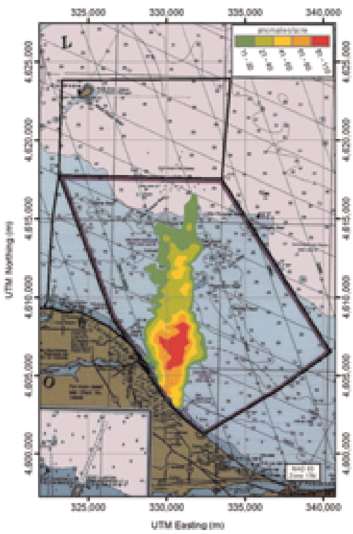


FIGURE 3

Estimate of the extent and density of munition contamination in Lake Erie associated with the Former Erie Army Depot. These data suggest that approximately 300,000 anomalies could potentially be associated with munitions in an area encompassing approximately 8,000 acres. (source: McDonald, 2007).



AUV costs are decreasing and may become economically viable alternatives to divers or ROVs. A recent trade-off study performed as part of a Strategic Environmental Research and Development Program research project (Foley, 2006) divided AUVs into five general classes based on operating mode (hovering, gliding) or diameter. The 22 (9 inch), 30 (12 inch), and 53 cm (21 inch) diameter AUV classes, summarized in Table 2, are feasible for munition inspections.

Removing Munitions

Specific circumstances factor in deciding if munitions must be removed, and if so, what methods and technologies would be cost efficient and would ensure safety for personnel and the surrounding environment. Munitions are only removed by necessity of the response action, when they are safe to move, and when they are to be transported for immediate disposal elsewhere or for storage for future disposal. When the risk of movement is not acceptable, a decision must be made whether the munitions is to be disposed in place or left in place.

There are four key criteria for selecting a recovery technology: (1) complying with applicable safety and environmental requirements, (2) meeting operational capabilities, (3) developmental stage, and (4) cost. Under the National Defense Center for Energy and Environment, recovery technologies were identified and researched. Table 3 summarizes several technologies that can be used to remove underwater munitions.

The process of removing underwater munitions can be complex and expensive. It involves complicated operations, requires trained operators, and must be safe for the workers, the public, and the environment. Because every site is unique, removal operations are also unique, often posing different challenges that must be addressed. Some site characteristics to consider include the number and type of munitions, the munitions configuration (i.e., whether the munitions are fuzed and armed), the munitions condition (e.g., deteriorated, encrusted by sea life, buried in full or part), geologic characteristics of the sea floor (sandy, rocky, etc.), operational environment (the water's depth, visibility, wave action, currents, wind), and the need to protect the marine habitat and threatened or endangered species. These characteristics drive site-specific operational requirements for recovery technology, as well as the safety considerations for people and the environment. The DoD emphasizes the use of remotely operated technologies

TABLE 2

AUV tradeoff study (Foley, 2009).

	9 Inch	12 Inch	21 Inch
Standard depth rating (m)	100	300–1,500	3,000
Length (cm)	165	335	356
Mass (kg)	62	159	183
Top speed (m/s) (kts)	2.57 (5)	2.57 (5)	2.57 (5)
Average speed (m/s) (kts)	1.54 (3)	1.54 (3)	1.8 (3.5)
Endurance at average speed (hours)	20	24	30
Launch and recovery System required	N	Y	Y
Available Modular Sensors			
Doppler velocity log (DVL)	Standard	Standard	Standard
Side scan sonar (SSS)	Y	Y	Y
Front looking sonar (FLS)	Y	Y	Y
Low light video	Y	Y	Y
Still camera with lights	Y	Y	Y
Sub-bottom profiler			Y
Fluorometers		Y	Y
Conductivity, temperature, depth (CTD)	Y	Y	Y

because, as a rule, their use greatly increases safety and operations can normally proceed around the clock.

Although there is limited experience with recovering underwater munitions, land-based munition responses, which have been performed for over 15 years, provide information that can be used to help guide underwater recovery operations. Munition sites where over the side disposal operations were conducted and sites used as proofing ranges, such as Ordnance Reef in Hawaii and the Former Erie Army Depot, respectively, are likely to have large numbers of unfuzed munitions spread over large expanses of the water bottom. The challenges for such sites are selecting highly maneuverable technologies and designing recovery and supporting operations capable of efficiently managing large numbers of munitions. The challenge at former live fire training ranges is the potential presence of UXO that poses imminent explosive hazards. The number of UXO in these ranges is likely much lower compared to the numbers of DMM in disposal areas. One added difficulty is the likelihood the UXO is commingled with very large quantities of fragments from munitions that functioned properly. In these scenarios, the recovery technology should be highly maneuverable and removal operations must be designed to address the hazards posed by UXO.

Disposing of Munitions

The recovery of underwater munitions does not, of itself, resolve any associated explosive safety hazards. Once recovered, these munitions must be disposed of in a safe and environmentally friendly manner, which may include open detonation. Disposing of recovered munitions can be difficult to plan because a number of factors must be considered, including worker and public safety, disposal location, and disposal method. When the disposal method makes use of a barge or ship, the disposal process can become more complex. Disposal operations must comply with applicable federal and state laws and regulations, as well as applicable DoD and Service policies, including the DoD Ammunition and Explosives Safety Standard (DoD, 2008).

Blow-in-place (BIP) and consolidated shots do not involve removing and recovering munitions and are the most common disposal practices. A consolidated shot is similar to BIP except numerous munitions are disposed at the same time and at the same location. BIP and consolidated shots are selected when it is unsafe to move munitions or unsafe to transport them large distances or to off-site disposal locations. These options destroy munitions using a donor explosive charge placed immediately on or adjacent to the munitions. These disposal techniques have inherent hazards associated with them as they expose workers to explosives during the disposal operation. However, BIP and consolidated shots put the disposal crew in full control of the donor explosive and its detonating sequence during the entire disposal operation. It must be stressed that BIP and consolidated shots are generally the safest disposal methods because they expose the smallest number of workers to explosive hazards for the shortest amounts of time. They do, however, also have the greatest potential to harm the underwater ecosystem because of blast effects. To address this concern, a recent study performed by the Space and Naval Warfare Systems Center (Wild, 2009) demonstrated that bubble curtains significantly reduce blast pressures outside

TABLE 3

Undersea munitions recovery technology summary.

Technology	Safety/Environmental Features	Operational Capabilities	Equipment Specifications	Personnel	Costs	Relocation/Mobility	Developmental Stage
ROUMRS	Remote surface operation Remote munition characterization capabilities Munitions remain under surface and are towed to disposal site	Depth: 300 feet (adaptable to 1000 feet) 24/7 operation, 1 h maintenance per 12 h operation Munitions capacity: 0.50 cal to 155 mm (can be modified to 2,000 lbs)	ROV, manipulators, sonar, camera system, laser scaling, multi-beacon, recovery basket. Magnetometers and chemical sensor suite available. 55 to 75 foot surface vessel	2 persons/12 h plus vessel crew	Capital: $800,000 Relocation, setup, demobilization: $100,000 O&M: $900,000-1.2 million/month	Mobile system. Ship ground, rail, or sea in 20 feet ISO container. Approximate 2 week transit time	All commercially available components. Has not been assembled. Can be ready to demonstrate in 10 months
Munitions Recovery System, UXB	Remote surface operation Munitions remain in containment units until disposal. Explosion- proof sealed containment chamber for munitions transport, and destruction	Depth: 500 feet 24/7 operation: 1/2 shift per week maintenance Munitions capacity not provided at this time. Munition locating technologies	ROV, camera system, and sealed containment system. Large surface vessel for controls and to house munition containment unit	4 persons/8 h/3 shifts; 2 for ROV, 2 for DynaSafe (if required)	Capital: None (long term lease required) Relocation: $450,000 Setup: $227,000 O&M: $961,000/ month	Mobile system. Relocation method not provided at this time	Technology demonstrated for the British Royal Navy The containment system is commercially available
Ordnance Recovery System, UOR	Remote surface operation Munitions remain under surface and are towed to disposal site	Depth: Over 250 feet 24/7 operation: 4 h maintenance per 40 h of operations Demonstrated with 500 lb practice munitions in 30 feet water	Sea floor crawler ROV with grapple, surface controls, and camera system. Surface vessel with 32-ton lift capability and additional small craft support vessels	5 man crew plus vessel and small craft crew	Capital: $15 million basic system cost $5 million site specific equipment Setup: $162,000 O&M: $1.855 million/month	Mobile system. Palletized for shipping. C-17 transport or trucks	Technology demonstrated in sea trials in Key West, FL in 2005 to remove two 500lb practice munitions from 30 feet depth. Demo ready in 4 months

Continued

Technology	Safety/Environmental Features	Operational Capabilities	Equipment Specifications	Personnel	Costs	Relocation/Mobility	Developmental Stage
MURS ESTCP Project MM-0732	Remote surface operation	Depth: Under 20 feet Operation times and maintenance schedules are not available Demonstrated with 2000 lb munitions	Government owned AOE System, electromagnet, electrical cables, power generator, camera system, control system. Surface barge/ vessel capable of supporting sur face equipment	One operator plus vessel crew	Cost determinations are still in progress	Mobile system. Requires shipment of AOE system, electromagnet and controls. Generator and support vessel hired on site	System is not commercially available. This system was demonstrated on land-based UXO removal with limited underwater testing
Efficient Shallow Underwater UXO Retrieval ESTCP Project MM-0606	Remote surface operation with protective shroud	Depth: Under 20 feet	Electromagnet, winch/crane, electrical cables, power generator, control system. Surface barge/ vessel capable of supporting surface equipment	One operator plus vessel crew	Cost determinations are still in progress	Mobile system. Requires shipment of electromagnet and controls. Winch/ crane, support vessel hired on site	System is in development. Possible demonstration mid-summer 2008. The system is operational at this time, and no further development currently planned after Fall 2008.

Continued

Technology	Safety/Environmental Features	Operational Capabilities	Equipment Specifications	Personnel	Costs	Relocation/Mobility	Developmental Stage
Diver operations	Diver is exposed to potential injury while working with munitions, minimal safety precautions are available. Close interaction with the munitions increases safety concerns for personnel, but may minimize the impact to surrounding marine environment	Limited to commercial diver depths and permissible diver bottom times. Limited by visibility	Dive equipment, dive vessel, lift bags, lift baskets. Vessel and equipment for towing lifted munitions to remote disposal site	Divers plus dive support crew and vessel crew	Costs determined by vessel operations costs and dive team costs. Capital costs for lift bags or lift baskets begin at about $5,000	Mobile, with minimal constraints on shipping and relocation	Fully developed
Dredging	Remote or manual operation with appropriate blast shielding Dredging is not protective of the marine environment. Design of the munition recovery portion of the operation is protective of workers and the environment.	Clam shell dredge depths are limited only by their cabling and design. Suction dredge operational depths of 80 feet exist, common operational depths are between 40 and 50 feet.	Dredge equipment with associated barge or vessel, anchoring system, hopper barges with tugs (clamshell) or piping (suction), munition recovery facility or system, settling ponds or retention ponds for suction dredging	Dredge crew, munitions recovery crew, dredge spoils handling crew	Capital costs are in the tens of millions of dollars. Mobilization costs will vary from about $1 million to $8 million Operations costs can range from $0.35 to $20 per cubic yard, more if the sediments are contaminated with chemical constituents	Dredges are mobile within the constraints of navigable waterways. Overland transport of smaller dredges is done but is not common	Fully developed

All but the diver and dredging technologies information was prepared by the National Defense Center for Energy and Environment (NDCEE) (NDCEE, 2009). Information on diver and dredging operations was obtained from USACE (2009).

the curtains. Additionally, National Defense Canada uses bubble curtains to mitigate blast effects when disposing of underwater munitions using BIP.

Controlled or explosive detonation chamber technology provides relatively new capabilities that are now available in the commercial market. Such technologies include chambers specially designed to contain the blast and fragmentation from munitions placed and detonated inside the chamber. Some such technologies are designed to contain and subsequently neutralize any releases. Japan is using contained technology for the destruction of munitions recovered from Kanda Harbor, Japan. During these operations, Japan has disposed of thousands of World War II-era discarded chemical munitions recovered from the harbor floor (Hayashi, 2009). Because few underwater munition recovery operations have been conducted in U.S. coastal waters, controlled or contained technology has not yet been used to support such operations. However, this technology could be mounted on a barge to dispose of munitions recovered from the sea floor. Because contained detonation chambers are only rated to handle specific net explosive weights, larger munitions may need to be reduced in size using other technologies (e.g., water-jet cutting).

Other Options for Munition Response Disposal and Management

Less common is the low-order BIP, which challenges munitions using an explosive jet-perforator, and water-jet cutting. The former has been tested and shown success in igniting explosives within the munitions without causing a full high-order detonation (i.e., explosion) (Pederson, 2002), although its use beyond the demonstration testing is unknown. Water-jet cutting is performed on a production basis on a limited number of land sites, and a single underwater COTS system was identified from a United Kingdom firm. Its use is undocumented in the United States.

Capping (e.g., entombment with cement, covering with riprap) is not a disposal technology but helps prevent human contact and serves to reduce any potential interaction between people and underwater munitions. Capping mitigates but does not remove or eliminate any potential explosive hazards. Additionally, it does not address the potential impact from munition constituents that may be released into the marine environment, although some new approaches are being developed that may address such releases.

Remediation of munition constituents has not been a significant concern to date. As more sites are investigated, and should unacceptable risks be identified, it may become important. Two potential in-situ remedial technologies have been identified. One promotes rapid, in-situ chemical degradation of munition constituents into benign breakdown products. The other employs microbial mats, which are complex communities of bacteria and algae that use photosynthesis to degrade munition constituents. These technologies are currently only conceptual for their potential applicability to underwater munition response and have yet to be demonstrated or validated in underwater environments. Dredging is the only other alternative that can remove sediments contaminated with munition constituents. Dredging technologies are summarized in Table 3.

Sampling for Munition Constituents

Sampling for munition constituents is usually performed after an area has been identified with munitions on or beneath the sea floor. Collecting water and sediment samples at shallow depths is straight forward, and technologies for doing so are well established; however, collecting samples from a deep-water site where sampling at a set distance from munitions or munition clusters is much more complex. Water-column and ponar grab samplers are common and can very quickly collect water or sediment for sampling and shipment to laboratories for off-site analyses. Some ROV-mounted sampling systems do exist but are not common. Gravity coring and vibracoring are also mature technologies and can collect sediment cores of several meters to 10 m or more in length. Gravity and vibracoring require a crane or hoist to lift the systems as well as being capable of pulling the core from the sediment.

In-situ sampling is limited to sampling water, and three types of systems are known: ion mobility spectroscopy, gas chromatograph-mass spectrometry (GC-MS), and amplifying fluorescent polymer (AFP). All three detect explosive compounds and rely on explosive molecules emanating from the munitions into the surrounding water. COTS systems are not yet readily available, but several AFP systems and one GC-MS are in use. Information on the theory and mobility of trace explosives chemicals is available (Woodfin, 2007).

Navigation and Underwater Positioning

Knowing where sensors take measurements and getting divers, ROVs, or AUVs back to a specific spot on the water bottom are critical aspects of underwater munitions operations. The challenge is to accurately locate where anomalies are detected and then return to the anomaly locations. Positioning errors from each phase of work are additive through the sequence of operations, starting with the geophysical mapping, followed by selecting targets of interest, and then reacquiring those targets for inspection, removal, or disposal. Differential global positioning systems (GPS) or real-time kinematic GPS are very common for vessel positioning and navigation, but GPS does not operate underwater and cannot be used directly to locate underwater sensors, divers, or platforms. Land-based operations are usually designed to minimize total positioning errors to between 50 cm and 1 m. Larger errors, particularly when working in areas of high concentrations of clutter (e.g., fragments of functions munitions), significantly drive up clean-up costs and, if not controlled, can reduce the certainty that all munitions are actually recovered. Some commercial underwater positioning systems deliver accuracies of about half a meter to a meter in shallow water. Accuracies of several tens of meters are typical in deep waters.

Lay-back, long baseline (LBL), or ultra-short baseline (USBL) acoustic positioning, inertial navigation systems, and Doppler velocity logs are common for underwater positioning and navigation. Table 4 summarizes demonstrated positioning accuracies for some of these technologies in a controlled environment at Aberdeen Proving Ground in 2005 (U.S. Army Environmental Quality Technology, 2006).

All individual components of any given system have inherent accuracy errors that can be quantified and minimized through planning and design. It is critical to understand capabilities and limitations of all components deployed during munition response projects, and it is equally important to design tests that demonstrate if expected accuracies are being met.

Conclusions

There is a need to recognize that numerous technology options are available to meet project needs during each phase of the response process. Some of these technologies are well understood, available on the commercial market, and easily deployed to address operational requirements. However, some technologies have only recently been applied in locating and defining the boundaries of munition response sites and determining the potential hazards posed from underwater munitions, and the DoD and industry are still learning how

TABLE 4

Summary of estimated precisions and estimated accuracies for marine positioning systems (modified from U.S. Army Environmental Quality Technology, 2006).

Positioning System	Deployment Conditions	Estimated Precision[a]	Estimated Accuracy[b]
Lay-Back (e.g., MagLogNT Interpolator or MagMap2000)	Fixed array (e.g., hard-mounted to vessel), no waves	Typical: 2 to 5 cm	Typical: 10 to 20 cm
		Range: 0 to 10 cm	Not determined
Lay-Back (e.g., MagLogNT Interpolator)	Towed array, no waves	Typical: 5 cm	Typical: 25 cm
		Range: 0 to 10 cm	Range: 0 to 50 cm
Lay-Back (e.g., MagLogNT Interpolator)	Towed array, simulated waves	Typical: 15 cm	Typical: 35 cm
		Range: 0 to 25 cm	Range: 0 to 70 cm
USBL (e.g., ORE Trackpoint II Plus)	Towed array, no waves	Typical: 35 cm	Typical: 25 cm
		Range: 15 to 60 cm	Range: 0 to 50 cm
USBL (e.g., ORE Trackpoint II Plus)	Towed array, simulated waves	Typical: 50 cm	Typical: 60 cm
		Range: 20 to 80 cm	Range: 20 to 1 m
LBL (e.g., AquaMap)	Towed array, no waves	Typical: 10 cm	Typical: 15 to 50 cm
		Range: not determined	Range: not determined

[a]Precision in this report is defined as point-to-point relative precision.
[b]Accuracy in this report is defined as the accuracy of an interpreted anomaly's location compared to its actual source location, in geographic coordinates.

to optimize these technologies for munition-specific applications. Lastly, DoD-funded research and development are delivering new products to detect, remove, and safely dispose of underwater munitions.

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